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Electron Impact Ionisation in Semiconductors.

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Abstract.

Experimental facts are presented showing that the quantum yield of the inner photoelectric effect increases if the photon energy exceeds a certain value. This is interpreted as due to the intrinsic electron impact ionisation. A theory of this effect is discussed. The relation of the high energy quantum yield to the low energy parameters is shown. Some other effects related to the intrinsic impact ionisation are mentioned.

If the kinetic energy of an electron or a hole attains a certain value an interaction with the valence band electrons can take place leading to the generation of a new electron-hole pair. In semiconductors this intrinsic impact ionisation was first observed in the breakdown of silicon [1-5] and germanium [6-8] p-n junctions. Considering the breakdown as a solid state analog of the Townsend β-avalanche breakdown in gases it was possible to deduce some fundamental information on the impact ionisation process.

1. Experimental Studies of the Quantum Yield.

We have dealt with this effect from another standpoint studying the dependence of the quantum yield of the inner photoelectric effect on the energy of the absorbed photon. The quantum yield η is the number of the electron-hole pairs created on the absorption of one photon. It was known from the measurement with low energy photons that the quantum yield near the infrared limit is one. From the measurement with high energy photons in the region of X - rays it followed that η is proportional to the energy of the photon [9] or, in other words, in this region the energy needed for the creation of one electron-hole pair is constant (in Ge ε = 2.5 eV). It was obviously of interest to study the transition between the two regions. The measurement was performed by Koc [10] (Fig.1). Similarly as in the work [9] he used the photovoltaic effect in a germanium p-n junction. It is apparent that the quantum yield η increases with the photon energy E_γ if it exceeds the value E' = 2.2 eV. The tangent at the point $E_\gamma = E'_\gamma$ passes through the origin. It is remarkable that its slope is nearly the same as the slope of the corresponding straight line $\eta = \eta\ (E_\gamma)$ in the X-ray region. A more detailed examination of the curve reveals a certain structure the nature of which can be shown more clearly in InSb (see below).

The measurement of η in Ge was recently repeated by Vavilov and Britain [11] by a similar method. They have found qualitatively the same curve but the critical energy E'_γ was found to be 2.9 eV. The difference is probably due to different methods of measuring the reflectivity. Vavilov and Britain measured the reflectivity using a hollow sphere coated with MgO thus taking

into account diffused light which was neglected by Rao.

Recently, Vavilov and Britsin have measured the quantum yield in silicon by a similar method; the energy E_γ' was found to be about 3.25 eV [12].

The uncertainty in the reflectivity is much smaller with InSb where it is practically constant near the energy E_γ'. With this material it is difficult to use the p-n junctions but it is easy to measure the photomagnetoelectric and the photoconductive effects. The former effect increases with increasing absorption coefficient, the latter decreases. If the two effects have the same dependence on E_γ it is considered probable that the change of the absorption coefficient with E_γ has negligible influence on the result. This was the case in our measurements [13], a typical result of which is in Fig. 2. The increasing of η with E_γ starts at $E_\gamma' = 0.47$ eV at room temperature. The tangent at this point passes again through the origin but the rise in the curve soon diminishes and even stops. At the energy $E_\gamma'' = 0.6$ eV η starts to increase again with a lower slope than at the point E'. Although the exact shape of the curve was not well reproducible with different samples and surface treatments nevertheless the points E', E'' were always noticeable. They move towards higher values with decreasing temperature; the order of magnitude of this change is 10^{-4} eV/grad.

2. Irradiation with Electrons.

The quantum yield was also determined in the high energy region with irradiation by fast electrons [14-16] and α-particles [17,18]. These measurements gave values of ε somewhat higher

(5 eV or more) than the above-mentioned value of 4.5 eV determined with ultraviolet. We have tried to measure η in germanium with low energy electrons. Lee [19] used the electron-voltaic effect in germanium p-n junctions (grown or alloyed). The measurements showed the existence of a certain threshhold energy E_{min}, below which no signal was observed. For the energy of the electrons $E > E_{min}$, η is a linear function of E. The threshhold energy E_{min} is several hundred volts and changes with the condition of the surface.

We suppose that E_{min} corresponds to the energy necessary for the electrons to penetrate through the oxide layer on the surface. The estimate of the thickness of the layer based on this assumption agrees with that obtained by other methods (tens of Angstroms).

Ehrenberg et al. [20] have found an energy threshhold of several thousands of eV in selenium barrier layer cells. Li Tschi-Tsaian has bombarded CdS and CdSe polycrystalline layers with very slow electrons and measured the changes of the conductivity [21]. He has found a very low threshhold of the incident energy (tenths of an electronvolt) and abrupt jumps in the signal at the multiples of the energy gap (2.5 eV in CdS, 1.8 eV in CdSe).

3. Interpretation of the Low Energy Curve.

The observed dependence of η on E_γ can be explained by the following mechanism. On the absorption of a photon an electron in the conduction band and a hole in the valence band are created which have in the first moment excess kinetic energies. If these energies are lower that the ionisation energies necessary for the creation of a new electron-hole pair they are

transferred to the lattice and lost. If the kinetic energy of an electron or a hole exceeds the ionisation energy new pairs are created by an impact ionisation and the quantum yield is larger than one. The number of the created electron-hole pairs increases with the excess energies of the electron E_n or the hole E_p.

A theory based on this idea was worked out by Antončík [22]. He considers the ionising action only of the electrons in the conduction band. The minimum energy $E_{n,ion}$ which an electron must have to be able to ionise the valence band electrons is determined by the conservation laws for energy and crystal momentum in the process

1 fast electron $\longrightarrow$ 1 hole + 2 electrons

$E_{n,ion}$ depends on the band structure. With a somewhat schematised model of the band structure Antončík obtained for Ge $E_{n,ion} = 0.82$ eV $= 1.24\ E_G$, for Si 1.25 eV $= 1.14\ E_G$ [22].

Antončík then calculates the number of electron-hole pairs created by impact ionisation in the neighbourhood of $E_{n,ion}$, assuming that a fast electron can ionise only once. If the band structure is not spherically symmetrical (as is the case for Ge, Si, InSb) the conservation laws are fulfilled for $E_n = E_{n,ion}$ only in a finite number of directions in the Brillouin zone. In Ge these are the (111) directions connecting the centre of the zone with the minima of the conduction band. Antončík then shows that if $E_n > E_{n,ion}$ the conservation conditions hold in a certain solid angle around the starting (111) direction which increases with E_n. Supposing that all electrons in this solid angle give new pairs by ionisation, one obtains for the number

of the pairs created by impact ionisation (corresponding to one absorbed photon):

$$\eta_{ion} = \frac{s}{2\sigma} \frac{1+\alpha}{D} \frac{1}{E_{n,ion}} \left(E_n - E_{n,ion} \right) \qquad (1)$$

This formula holds for schematised "many valley" conduction bands such as these of Ge and Si, s is the number of minima in the conduction band, the number of ellipsoids ($\sigma = \frac{1}{2} s$ for Ge, $\sigma = s$ for Si), α and D are parameters depending on the band structure ($\alpha = 0.221$, $D = 1.242$ for Si, $\alpha = 0.303$, $D = 1.529$ for Ge [22]).

The ionisation actually starts at some energy $E_n^* > E_{n,ion}$ owing to the interaction of the electron with the lattice. As the cross-section for the impact ionisation very steeply increases with the electron energy E_n (once it exceeds $E_{n,ion}$) whilst the cross-section for the interaction with the lattice slowly varies with E_n, the energy E_n^* should not differ much from $E_{n,ion}$ (some tenths of an eV [22]).

In principle, similar considerations should hold for the impact ionisation by holes.

If we are going to apply these considerations for the determination of η the question arises how are the energies of electrons and holes distributed just after the absorption of a photon. This is a difficult problem not solved yet. Antončík [22] makes a very rough assumption that in Ge the electron takes all the excess energy. Using Eq (1) one obtains for the quantum yield for E_γ slightly larger than E_γ^* :

$$\eta = 1 + \eta_{ion} = 1 + \Delta \left(E_\gamma - E_\gamma^* \right), \qquad (2)$$

where $\Delta = e\,(1+\alpha)/2\sigma$ $DE_{n,ion} = 1\ eV^{-1}$. This is in reasonable agreement with experiment. The energy $E_n' = E_\nu' - E_G$ 1.5 eV is considerably higher than $E_{n,ion} = 0.82$ eV and agrees with the value determined from the breakdown of the p-n junctions by Miller [6]. Using the same argument for Si we get with the data from Vavilov and Britsin [12] $E_n' = 3.25 - 1.1 = 2.25$ eV which is in better agreement with the result obtained by Chynoweth and Mc Kay [5] (2.25 eV) than with that by Miller [4] (1.5 eV).

The assumption that the electron has all the excess energy is certainly not well fulfilled in Ge and Si and we should expect that the actual values of E_n' are somewhat lower. But it may be a very good assumption for InSb where the effective mass of an electron is far smaller than that of a hole. The observed curve $\eta = \eta\ (E_\gamma)$ in Fig. 2 could be explained by a band structure schematically suggested in Fig. 3. For small energy differences $E - E_G$ practically all the energy $E_\gamma - E_G$ is taken by the electron. With increasing $E_\gamma - E_G$ the holes obtain a larger and larger part of this energy. This energy is lost as long as the holes do not attain the ionisation energy. Therefore in this region the initial rise of η with E_γ slows down and eventually stops. As soon as the holes are able to ionise η starts to increase again (at the point E_ν'').

An essential point in the theory of Antončik is the anisotropy of the band structure. For a spherically symmetrical band structure η should change abruptly at E_ν' (similarly as was observed in ref. [21]).

4. High Energy Region.

By further increasing the photon energy we get into a region where at present there is neither experimental nor theoretical information available. The situation is simple again at high energies $E_\gamma \gg E_G$ where η is proportional to the energy of the photon or the particle. We may assume that in any case high energy electrons are first created which loose their energy by impact ionisation. The process is undoubtedly complex and complicated by emissions and reabsorptions of photons. However if we take the energy losses by secondary X-ray emission into account we find that the net energy ε needed for the creation of an electron-hole pair is little dependent on the energy of the photon [9]. It follows that electrons with high energies ($E_n \gg E_n'$) transfer little energy to the lattice. This is also to be expected on simple theoretical considerations.

By successive ionisation processes the energies of the electrons and holes finally sink under E_n', E_p'. If we suppose that no losses to the lattice occur for $E_n > E_n'$, $E_p > E_p'$ we have

$$\varepsilon = E_G + \langle E_n \rangle + \langle E_p \rangle \qquad (5)$$

where $\langle E_n \rangle$, $\langle E_p \rangle$ are the mean values in the intervals $0, E_n'$ and $0, E_p'$. Supposing, as is occasionally done [4, 5], that the energy is uniformly distributed in these intervals we have

$$\varepsilon = E_G + \tfrac{1}{2} E_n' + \tfrac{1}{2} E_p'.$$

The value determined by E_ϱ (3) must be considered as the lowest limit of ε. We know from the measurement of η that not all electrons and holes with energies somewhat greater than

E_n', E_p' can ionise. A part of the energy in this region is necessarily lost to the lattice. Using here the experimentally determined parameters we can calculate $\mathcal{E}$ supposing we know the distribution of the energies of electrons and holes. This is a rather difficult problem not yet satisfactorily solved. The relation between the high and low energy effects are being experimentally and theoretically studied in our laboratory.

5. Other Effects Related to Impact Ionisation.

Most of the information on the ionisation process during the breakdown of p-n junctions was obtained by an analysis of the electrical data. However, it is to be expected that interesting facts, especially on the energy distribution of electrons and holes, may be deduced from the study of electroluminescence [23,24] and external electron emission [25, 26]. Important deductions were obtained by the study of the yield of the external photoelectric emission that appreciably diminishes if the energy of the excited electrons attain the ionisation energy [27].

Recently Landsberg has been able to predict the rise of the quantum yield with E_y in InSb from a comparison of the radiative lifetimes determined by direct measurement of the radiation or by calculation from the optical constants [28].

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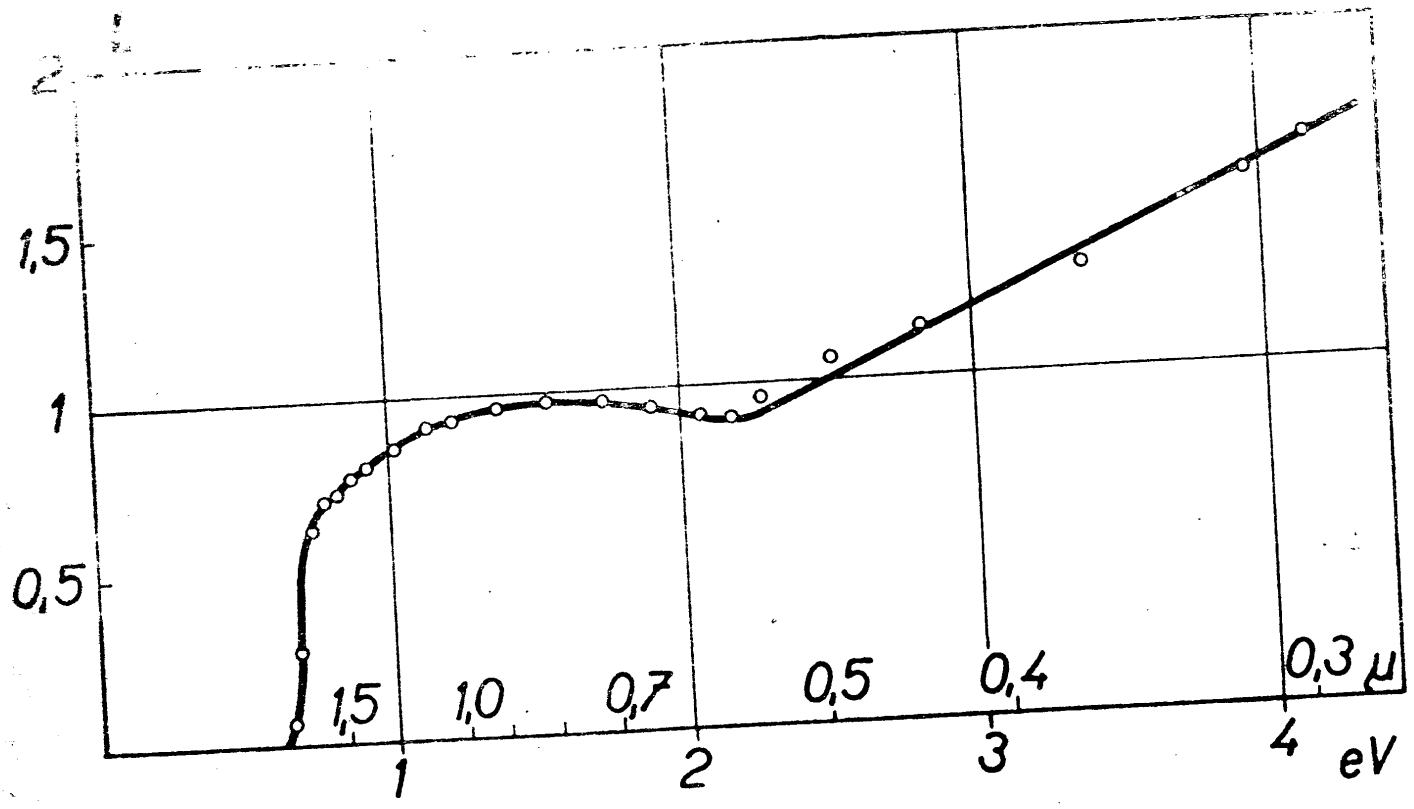
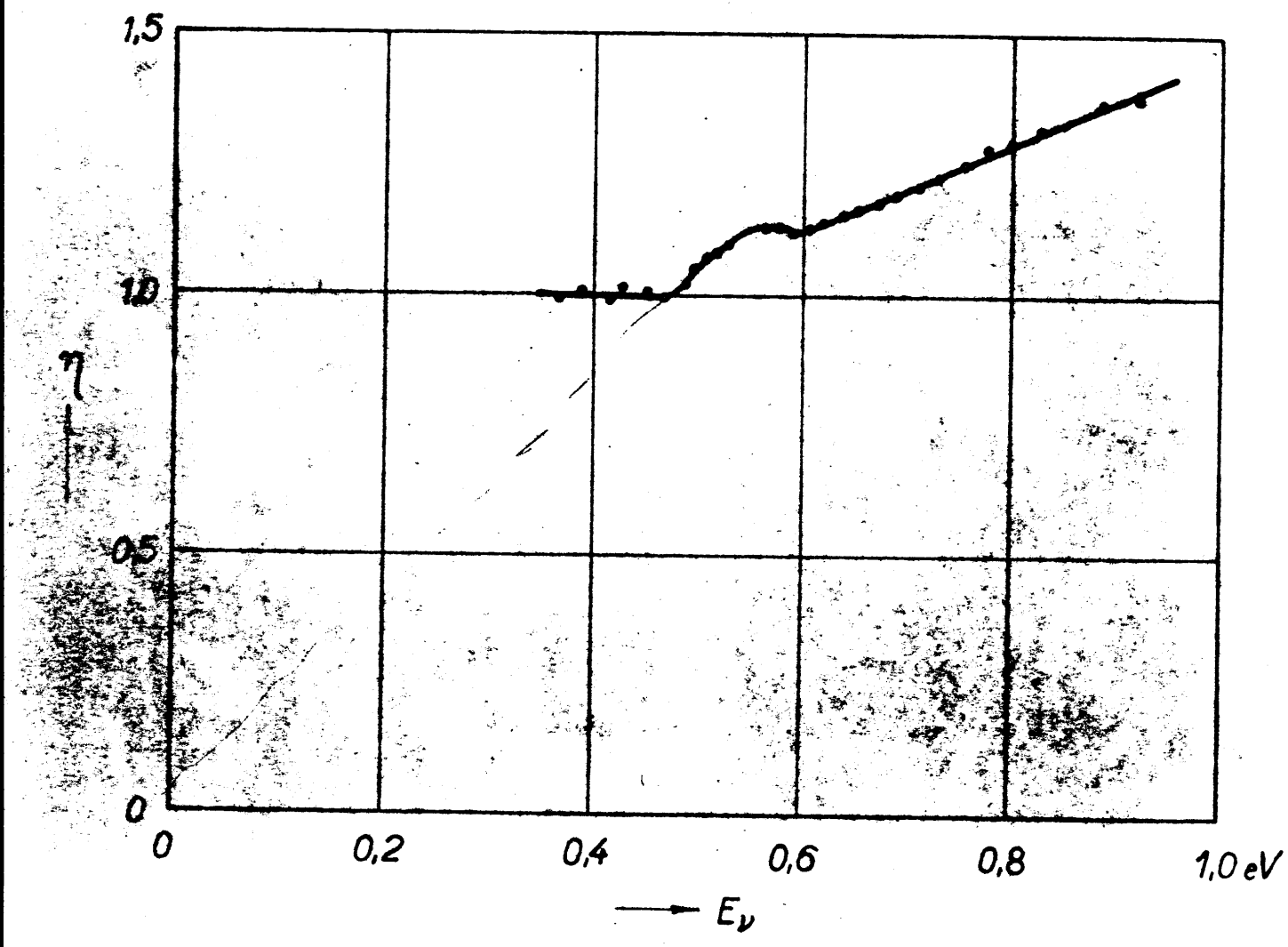
Text to the Figures.

Fig. 1 - Quantum yield η in Ge as a function of the energy of the photon E_γ

Fig. 2 - Quantum yield η in InSb

Fig. 3 - Suggested band structure of InSb to explain qualitatively the curve given in Fig. 2.





Tauc, Fig. 3